7. TROPICAL CYCLONE (TC) SUPPORT SUMMARY

7.1 SOUTHERN HEMISPHERE APPLICATION OF THE SYSTEMATIC APPROACH TO TROPICAL CYCLONE TRACK FORECASTING

Author: Russell L. Elsberry
Naval Postgraduate School
Monterey, CA 93943

The environment structure conceptual models of the Systematic Approach to Tropical Cyclone Track Forecasting technique of Carr and Elsberry have been applied to all Southern Hemisphere tropical cyclones during January 1994 - June 1997. Whereas three of the four synoptic patterns from the western North Pacific could be applied with relatively small modifications, a new High (H) amplitude synoptic pattern was defined to classify the situations with large meridional penetrations of mid-latitude troughs deep into the Southern Hemisphere tropics. Some changes in terminology were required to describe the synoptic regions that have characteristic track directions. All 1592 cases during the period could be described as existing within one or more of these four synoptic patterns and 11 synoptic regions. Important track changes were found to be associated with transitions between these synoptic patterns and regions. Three binary tropical cyclone interactions defined for the western North Pacific were adapted for use in the Southern Hemisphere with considerable success. A preliminary climatology of occurrences for the synoptic pattern/region combinations, transitions between combinations, and binary tropical cyclone interactions are calculated. Sequences of synoptic analyses related to the transitions are described to aid in the application.

7.2 STATISTICAL POST-PROCESSING OF NOGAPS TRACK FORECASTS

Author: Russell L. Elsberry
Naval Postgraduate School
Monterey, CA 93943

A statistical post-processing technique has been developed and tested to reduce the Navy global model (NOGAPS) track forecast errors for a sample of western North Pacific tropical cyclones during 1992-96. In addition to the basic storm characteristics, the set of 24 predictors includes various segments in the 00-36 hour NOGAPS forecast track as well as a 00-36 hour backward extrapolation that is compared with the known recent track positions. Another key piece of information is the offset of the initial NOGAPS position relative to an updated (here best-track) position that will be known by about 6 hours after the corresponding synoptic times, which is when the NOGAPS forecast is actually available for use by the forecaster. For the development sample, the adjusted NOGAPS track errors are reduced by about 50 nm (93 km) at 12 hours, 33 nm (61 km) at 36 hours, and 24 nm (44 km) at 72 hours. Independent tests with a 1997 western North Pacific sample, 1995-97 Atlantic sample, and 1996-97 eastern and central North Pacific sample of NOGAPS forecasts have similar improvements from the post-processing technique. Thus, the technique appears to have a general applicability to Northern Hemisphere tropical cyclones.

7.3 AUTOMATED TROPICAL CYCLONE FORECASTING SYSTEM

Authors: C.R. Sampson and A.J. Schrader, Naval Research Laboratory, Monterey CA 93943

The Automated Tropical Cyclone Forecasting System (ATCF) version 3.2 was installed at JTWC, NPMOC, and NLMOC. This version features the following capabilities: an improved conventional meteorological database - TEDS 3.52; electronic logs for forecast operations; web pages for use in ATCF system support and communications; ECMWF and NCEP NWP model data display; scatterometer and cloud track wind display; NOAA compliant four-quadrant wind radii capability; geographic labels, and Tropical Cyclone Formation Alert (TCFA) graphic overlay generation for use on Joint Maritime Command Information System (JMCIS) workstations. Current work is focused on ATCF 3.3, to be installed in the spring of 1999. This version should include the capability to forecast beyond 72 hours and be year 2000 compliant. These capabilities involve a redesign of the tropical cyclone database format and a significant number of code changes. The new database will have capability to store a number of tropical cyclone parameters such as: minimum sea level pressure; radius of outermost closed isobar; radius of maximum winds; maximum wind gusts and eye diameter. It should also be easy to incorporate more forecast periods and tropical cyclone parameters with this new format.

7.4 SSM/I TROPICAL CYCLONE STRUCTURE

Authors: Jeff Hawkins, Naval Research Laboratory, Monterey, CA 93943
Co-authors: Richard Bankert, Paul Tag, Naval Research Laboratory, Monterey, CA 93943,
Juanita Chase, Doug May, Ron Holyer, Naval Research Laboratory, Stennis Space Center, MS 93943, and
Marla Helveston, Analysis & Technology, Bay St. Louis, MS 39520

The Special Sensor Microwave/Imager (SSM/I) has a suite of passive microwave channels that enable it to penetrate non-raining clouds and map out tropical cyclone (TC) associated rain and moisture structure. This ability to detect rainbands, eyewall(s) and eye/center locations can significantly assist the analyst and typhoon duty officer (TDO) when upper-level clouds obscure geostationary and/or polar orbiter visible (vis) and infrared (IR) imagery. TC structure is valuable for positioning and understanding storm intensity. This information, as well as any intensity trend, can then be used to upgrade the confidence and accuracy of storm warnings/advisories.

The Naval Research Laboratory's Marine Meteorology Division in Monterey, CA (NRL-MRY) has been exploring new methods to extract additional information from the wealth already contained in TC SSM/I imagery. Initial focus has been aimed at the high resolution (12-15 km) 85 GHz channels that nicely map TC structure and readily depict storm rainbands, eyewall(s) and center locations. This has been done by processing over 1500 SSM/I passes coincident with TCs ranging in strength from tropical disturbances to super typhoons and, east of the dateline, CAT 5 hurricanes.

Results to date indicate the SSM/I can greatly assist the analyst locate the storm center when intensities are in excess of 30-40 kt. This threshold can change for given systems, but is used here as a generic number. The user should note that the cloud (and thus rain) organization for weak systems is poor at best and vis/IR data can be just as good and/or better than SSM/I data for trying to determine the center in the beginning stages of tropical systems. However, there is no upper bound for SSM/I capabilities, and it is useful with systems in the range of 150 kt-sustained winds. Particular note should be made that these SSM/I views are not constrained by central dense overcasts, shear or embedded centers that can cause problems with vis/IR imagery.

Two methods have been explored to extract TC intensities from automated analyses of SSM/I digital data. The first effort involves a neural network method which:

1) Uses 85 GHz, H-polarization brightness temperatures.

2) Represents the TC pattern in 85 GHz images via its Empirical Orthogonal Functions (EOF).

3) Trains the neural net with the EOFs most highly correlated with intensity.

4) Trains the net with a dependent storm data base using JTWC/NHC best track intensities.

The data base now contains over 750 TCs in the dependent data set and verification using "independent" cases has now shown skill ramping up storm intensity and weakening the storm as seen in real cases. The RMS error is still greater than our goal of 15 kts, but significant progress indicates this may become a viable technique within the next year.

The second effort utilizes computer vision capabilities to analyze both 85 GHz and rainrate products from the SSM/I. The same set of storms used to train the neural network is also used here. Spatial and textural measures, as well as those using various frequencies within the spectrum, were developed to extract features that are most highly correlated with TC intensity. Some of these features are analogous to those used within the Dvorak method, such as banding of particular temperature ranges, minimum brightness temperature, rainrates above a certain threshold, etc. Results to date indicate an RMS error less than 20 m/s and getting close to 15 m/s. Some large outliers exit, but many of them appear to be related to poor best track values. Note that no time averaging has yet been applied in either the neural network or computer vision methods.

Additional work, with well over 1,000 high quality storm hits, is underway. The Tropical Rainfall Mapping Mission (TRMM) Microwave Imager (TMI) and radar data will be added in the next update to this effort. TMI channels are basically identical to the SSM/I, with the addition of a low frequency 10 GHz channel that can assist with the determination of sea surface temperature and wind speed retrieval. TMI is mounted on a platform with an orbital altitude approximately one-half that utilized by the SSM/I platforms. This results in twice the spatial resolution (5 km) but half of the footprint (approximately 750 km). Also of note, the 35 degree orbit inclination will permit more frequent TC coverage compared to more typical polar orbiters such as the DMSP/NOAA suite of satellites.

7.5 TROPICAL CYCLONE SCATTEROMETER STUDIES

Authors: Jeff Hawkins, Naval Research Laboratory, Monterey, CA 93943, and Roger Edson, Analysis & Technology, Guam

The ERS series of scatterometers have provided the bulk of the active microwave surface derived wind measurements from space since the launch of ERS-1 in 1991. ERS-2 continued to produce a 500-km swath of surface wind vectors throughout JTWC's Area Of Responsibility (AOR) during 1997, using a frequency that permits wind retrievals even under rainy conditions prevalent with tropical cyclones (TCs). The 50-km spatial resolution is coarse, but can often be sufficient to specify the radii of gale force winds as well as help position storm centers. Storm positioning is especially important for the weaker developing systems, when cloud/rain patterns are poorly defined and knowledge of the surface wind field is critical is assisting the analysts to achieve their goal.

ERS-2's 500-km swath presents often clustered but infrequent TC overflights. TCs can often move for days before the next pass clips or passes sufficiently over the storm to provide useful data. This major limitation was partially mitigated with the availability of the NASA SCATterometer (NSCAT) in the summer of 1996. Although the satellite platform suffered a terminal power failure in the Spring of 1997, the instrument produced a wealth of surface wind vectors in two 600-km swaths, one on each side of the spacecraft. The percentage of swaths detecting TCs rose significantly when compared with ERS-2 and the "revisit time" between overflights for a given storm was reduced dramatically.

NSCAT surface winds proved very useful for specifying the radius of gale force winds and assisting in finding storm centers. Some problems were encountered in early versions of the wind retrieval algorithm and these improved with time. The spectral window utilized by NSCAT was not as impervious to TC rainbands and thus rain attenuation in heavy rain was troublesome. Although heavy rain should boost the backscattered return and create higher winds, cases were often found where the wind speeds were significantly reduced. Efforts are underway to utilize SSM/I and/or combined SSM/I-IR methods to map out rain areas that can then be used to incorporate attenuation corrections for enhanced wind vector retrievals.

NSCAT's premature termination has led to a new NASA program called QUIKSCAT. This new scatterometer will have frequencies similar to NSCAT, but will employ a rotating dish antenna instead of the multiple stick antennas for ERS and NSCAT. QUIKSCAT will have a major advantage in providing a contiguous 1800-km swath and thus remove the NSCAT problem of dealing with the 350-km gap that existed in the middle of the two 600-km swaths. Validation will occur during the winter of 98-99 and JTWC should have operational access to the data set by Spring of 1999.

7.6 UPPER TROPOSPHERIC OUTFLOW PATTERNS OVER SEVERAL VERY INTENSE TROPICAL CYCLONES OF THE WESTERN NORTH PACIFIC AS REVEALED BY SOUNDINGS, DOPPLER RADAR, AND WATER-VAPOR WINDS

Authors: Bill Ward National Weather Service, Tiyan, Guam and
Mark A. Lander, ONR-sponsored research at the University of Guam, Mangilao, Guam

As a warm-core vortex, the cyclonic circulation of a tropical cyclone (TC) weakens with height. In a mature TC, the peak winds occur within the lowest kilometer of the atmosphere. The intensity and areal extent of the cyclonic wind field decreases with altitude. In most text-book illustrations (e.g., Chen and Gray 1986), the cyclonic-flow region of the tropical cyclone is shown to decrease in size as one ascends to the upper troposphere, and in the outflow layer (above 200 hPa) the flow is depicted as predominantly anticyclonic.

Soundings from islands of the western North Pacific, vertical wind profiles of tropical cyclones obtained from Doppler radars located on Guam and Kwajalein, and water-vapor winds from the University of Wisconsin, have been collected during the lifetimes of several very intense tropical cyclones that have occurred in the western North Pacific. These data reveal that the extent of cyclonic circulation at upper levels is far more extensive than is commonly depicted, and that the signature bands and plumes of anticyclonically curved cirrus surrounding these tropical cyclones (which are unusually interpreted as evidence of antcyclonic outflow aloft) are not indicative of anticyclonic flow; but rather, they exist in cyclonically curved flow for several hundred km outward from the TC core, propagating outward and deriving their curvature from horizontal shear.

Outflow jets -- often referred to as outflow channels -- (another feature commonly thought to exist in the upper tropospheric flow surrounding TCs) are not found in our data set. Instead, broad areas of flow with an outward directed radial component (with respect to the cyclone center) nearly encircle the TC. Specific areas may contain somewhat enhanced flow, but these tend to be regions that are no smaller than a full quadrant of azimuth (in earth-relative coordinates). In storm-relative coordinates, the radially directed outward flow is even more symmetrical, and exhibits a decreased azimuthal concentration of outflow.

High-speed jet streaks existing at the periphery of tropical cyclones (usually marked by long cirrus plumes) have no concentrated links to the TC's core. Indeed, all airflow directed outward at upper levels from the tropical cyclone core appears to flow across a velocity minimum before it accelerates and enters these peripheral jets.

Some common tropical cyclone outflow patterns emerge from our data. They show that common operational estimation of tropical cyclone outflow from satellite imagery -- specifically, determination of the regions of good or poor outflow, and the assumption of the existence of outflow jets (or channels) based on the pattern of the cirrus cloud plumes -- is flawed.

7.7 SOME CHARACTERISTICS OF TROPICAL CYCLONE INTENSIFICATION AS REVEALED BY HOURLY DIGITAL DVORAK ANALYSIS

Author: Mark A. Lander, ONR-sponsored research at the University of Guam, Mangilao, Guam

One of the utilities installed on the satellite image processing equipment at the Joint Typhoon Warning Center (JTWC), Guam, is an automated routine for computing Dvorak "T" numbers for TCs that possess eyes. The routine adapts the rules of the Dvorak technique as subjectively applied to enhanced infrared imagery in order to arrive at an objective T number, or "Digital Dvorak" T number (referred to as DD numbers). In the western North Pacific, infrared imagery is available hourly from the GMS satellite. When applicable, hourly DD numbers were calculated for all typhoons of 1996 and some of the more intense typhoons of 1995 and 1997.

The evolution of the DD numbers for several of the more intense typhoons that occurred during 1995, 1996 and 1997, has revealed some characteristic changes that occur during the lifetimes of many of these TCs. In many cases, large fluctuations in the time series of the DD numbers can be correlated with changes in the structure of the eye -- the formation of concentric wall clouds being the most common type of change. Also, when compared with the TC's best-track data, other common features of the DD numbers emerge: during the intensifying phase of the TC, the DD numbers tend to rise more rapidly and peak earlier than the operationally determined T numbers from conventional subjective Dvorak analysis.

The characteristics of the time series of the DD numbers imply short-term fluctuations in the convective behavior of TCs. These fluctuations suggest that there may be corresponding rapid and large fluctuations in the TC's intensity. If real, this behavior has major ramifications for operational warning accuracy and for intensity research (which depends largely on best-track data for its intensity input and for its source of validation data). This also questions our knowledge of the rates of TC spin-up and spin-down in relation to the convective fluctuations. An exploration of the behavior of the DD numbers may lay the groundwork for future modifications to current methods of estimating tropical cyclone intensity from satellite imagery.

7.8 EVALUATION OF A SIMPLE TECHNIQUE FOR PREDICTING THE PEAK INTENSITY AND THE TIMING OF PEAK INTENSITY FOR TROPICAL CYCLONES OF THE WESTERN NORTH PACIFIC

Authors: G. McCulloch, S. Cocks, and P. Hildebrand, Joint Typhoon Warning Center, Guam, and Mark A. Lander, ONR-sponsored research at the University of Guam, Mangilao, Guam

In recent years, operational regional numerical models designed for tropical cyclone applications (e.g., the Japanese Typhoon Model (JTYM), and the model developed by the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton) have become capable of simulating realistic tropical cyclone structure, as well as the capacity for large magnitude intensity change that approach those which can occur in nature. Intensity predictions from real-time model runs are now routinely distributed to tropical cyclone warning centers. The level of skill of these intensity predictions (and of those made by the warning agencies) is difficult to evaluate since there are few simple baselines against which to compare them.

Many specific problems reside under the umbrella of tropical cyclone intensity forecasting. Presently, at JTWC, the forecaster is required to produce intensity forecasts in short (e.g., 12 hour) increments for periods of up to 72 hours. Additional forecast challenges remain largely unexplored such as the determination of the peak intensity and the timing of the peak intensity from a given stage in the development of the tropical cyclone. Contained in the widely used Dvorak techniques is a basic rule that an intensifying tropical cyclone intensifies at an average rate of one "T" number per day (up to a particular point). This corresponds to an increase of wind speed of approximately 20 kt per day. Dvorak also found that westward moving tropical cyclones are allowed a longer time in which to develop than are those that move northwestward. These, in turn, develop for a longer period of time than those tropical cyclones moving northward.

A simple technique (unpublished), developed by Mundell (a former typhoon forecaster at Joint Typhoon Warning Center, Guam), provides guidance in determining the tropical cyclone peak intensity and the timing of this intensity. He found that the time to peak intensity as measured from specific intensity thresholds, such as minimal tropical storm intensity (35 kt) and minimum typhoon intensity (65 kt), was a strong function of the latitude at which these thresholds were reached. Further, the magnitude of the peak intensity was also a function of the latitude of occurrence of the benchmark intensities (e.g., the lower the latitude of achieving minimal typhoon intensity, the higher the peak and the longer the time delay until peak).

The Mundell techniques also encourage the forecaster to consider parameters that are often not given as much thought as the track forecast, diagnostic intensity estimate, and short-range intensity predictions. These include issues such as the number of days will it take a particular TC to reach peak intensity; and the eventual peak intensity. Such statistics are not even routinely compiled in post-analysis. As efforts are made to provide better intensity forecasts, and to consider questions such as the peak and time to peak of individual TCs, the Mundell techniques offer a simple starting point for producing and evaluating forecast of these parameters, and for understanding the problem of TC intensity change.

7.9 A LOOK AT GLOBAL TROPICAL CYCLONE ACTIVITY: BASIN INTERCOMPARISONS AND RELATIONSHIPS WITH ENSO, QBO, AND OTHER LARGE-SCALE CLIMATE FEATURES

Authors: Mark A. Lander, and Charles P. Guard, ONR-sponsored reseearach at the University of Guam, Mangilao, Guam

The time series representing the annual tabulation of tropical cyclone (TC) numbers (from the annual global total, as well as the annual totals within individual ocean basins) appears highly erratic (i.e., there is no persistence and the values seem to jump substantially from one year to the next). Time-lag autocorrelations of these time series confirm this - all have small negative values at a one-year time lag. Also, most of the time series have prominent spikes of both exceptionally low and high values. The high years are referred to as 'prolific' years, and the low years as 'meager' years. The 'prolific' years and 'meager' years are identified within the global and basin distributions. The range in the annual TC numbers within any givin basin is large. The global annual average is 85 with a range of 66 to 105; the western North Pacific annual average is 27 with a range of 19 to 36; the North Atlantic annual average is 10 with a range of 4 to 19; the eastern North Pacific annual average is 16 with a range of 8 to 24; the North Indian Ocean annual average is 5 with a range of 2 to 13; and the Southern Hemisphere annual average is 27 with a range of 19 to 38. The difference of 39 between the maximum and minimum annual global number of TCs is more than twice that of any individual basin.

Given the relative rarity of TC formation (as a global atmospheric phenomenon) coupled with the aforementioned phenomenon of basin "prolific" and "meager" years, a natural question arises. Are there compensations among the annual individual basin TC numbers that act in a manner as to stabilize the global TC number (i.e., negative correlations among some or all of the TC basins); or is the annual global TC number destabilized by positive correlations among some or all of the TC basins? The latter appears to be true. Cross-correlations between the basins reveal weak positive correlations amongst the western North Pacific, eastern North Pacific, and the Southern Hemisphere. During the 27-year period 1969 to 1997 there were 16 years with at least one basin experiencing a "prolific" or a "meager" year. Five of these years had two, or more, "prolific" and/or "meager" years. Only two of the years (1969 and 1995) had different basins simultaneously qualified for both "prolific" and "meager" labels; the "prolific" years during these two years were those of the North Atlantic.

There are strong relationships of the annual number of tropical cyclones in the North Atlantic with El Niño Southern Oscillation (ENSO) and with the Quasi Biennial Oscillation (QBO). In other basins these relationships are weaker, and, at least with ENSO, the effects are primarily upon the locations of the TCs and not the annual numbers. Ongoing reasearch includes further exploration of the spatial and temporal properties of the global TC distribution and examination of the effects of ENSO, QBO, and other climatic features on the global and basin tropical-cyclone time series. The effects of the strong ENSO event of 1997-98 on the global TC distribution are receiving emphasis.

7.10 TECHNIQUES INCORPORATING SSM/I IMAGERY INTO DVORAK TROPICAL CYCLONE INTENSITY ESTIMATES

Authors: S.B. Cocks, and I. Johnson, Joint Typhoon Warning Center, Guam
Co-authors: Mark A. Lander and Charles P. Guard, ONR-sponsored research at the Univeristy of Guam, Guam

The Dvorak tropical cyclone intensity estimation technique for use on visible satellite data was introduced in 1975, with an additional technique for infrared satellite data introduced in 1984. The techniques have performed well throughout ocean basins across the world for nearly two decades of operational use. There are, however, cases where determination of the intensity of a tropical cyclone using the Dvorak methods has been inaccurate - particularly with the infrared techniques. This often occurs when the exact location and/or structure of the low-level circulation center is not known. Instances include the central dense overcast feature, the central cold cover, or the embedded center pattern (infrared imagery only). The Special Sensor Microwave/Imager (SSM/I) has the advantage of sensing through thick cloud cover, which can show the structure of a tropical cyclone that would otherwise be unseen in infrared or visible satellite imagery. SSM/I imagery can indicate the presence and location of low-level circulation centers and banding features; and can detect whether or not an eye is developing or already exists. These particular structural features of the TC are often not discernible in conventional satellite imagery. This study endeavors to develop similar rules for estimating the intensity of TCs using SSM/I imagery, and to explore ways to incorporate the SSM/I into Dvorak's conventional techniques- producing more versatile and accurate intensity estimates.

Using time matched visible, infrared, and SSM/I imagery in cases where the intensity estimate, given by Dvorak infrared or visible satellite methods, is clear-cut, features in the SSM/I imagery are found that are indicative of tropical cyclone intensity. There is clearly a relationship between TC intensity and specific properties as seen on microwave imagery. The SSM/I technique for estimating intensity was applied upon an independent set of tropical cyclones and the results were compared to those produced by established methods.

Results of the study so far indicate that subjective estimation of SSM/I imagery is possible; however, the accuracy of such estimates, on average, are not as good as those provided by the use of Dvorak's techniques on conventional visible and infrared satellite imagery. While it is possible that further research may uncover additional properties of microwave imagery that may allow a more accurate estimate of TC intensity, we feel that the biggest pay-off of the SSM/I imagery will come from providing a discipline to conventional Dvorak estimates of TC intensity. When the Dvorak intensity estimate for a given TC is not clear-cut, SSM/I imagery can provide valuable information that will allow one to arrive at a more representative estimate.

BIBLIOGRAPHY

Arnold, C.P., and C.C. Olsen, 1974: Tropical cyclone position and intensity analysis using satellite data. First Weather Wing Pamphlet 105-10, 97 pp.

Atkinson, G.D., 1974: Investigation of gust factors in tropical cyclones. Fleet Weather Center Technical Note: JTWC 74-1, 9pp.

______, and C.R. Holliday, 1977: Tropical cyclone minimum sea-level pressure and maximum sustained wind relationship for the western North Pacific. *Mon. Wea. Rev*., **105**, No. 4, pp 421-427 (also Fleet Weather Central/JTWC Technical Note 75-1).

Black, and F.D. Marks, 1991: the structure of an eye wall meso-vortex in Hurricane Hugo (1989). Preprints, 19th Conf. on Hurricanes and Tropical Meteor., AMS, Miami, FL, pp 357-358.

Brand, S., 1970: Interaction of binary tropical cyclones in the western North Pacific Ocean. J. Meteor. Soc. Japan, 50, pp 332-341.

Businger, S., and Baik, J-J., 1991: An arctic hurricane over the Bering Sea. *Mon. Wea. Rev*., **119**, pp 2293-2322.

Carr, L.E., and R.L. Elsberry, 1994: Monsoonal interactions leading to sudden tropical cyclone track changes. *Mon. Wea. Rev*., **123**, pp 265-289.

______, and ______, 1994: Systematic and integrated approach to tropical cyclone track forecasting, Part I: Description of basic approach. Naval Postgraduate School publication NPS-MR-002. Naval Postgraduate School, Monterey, CA 93943. 65 pp. plus figs. and append.

______, ______, and Boothe, 1997: Systematic approach to tropical cyclone forecasting: scenario-specific model and objective guidance traits. Preprints, 22nd Conference on Hurricanes and Tropical Meteorology. American Meteorlogical Society, Boston, MA.

______, ______,and ______, 1997b: Condensed and updated version of the systematic approach meteorological knowledge base – Western North Pacific. Tech. Rep. Naval Postgraduate School (in press).

Chen, L., and W.M. Gray, 1986: Global view of the upper level outflow patterns associated with tropical cyclone intensity change during FGGE. Dept. of Atmos. Science Paper No. 392, Colorado State University, Fort Collins, CO, 80523, 126 pp.

Climate Prediction Center (CPC), 1997: Graphical illustrations of global wind, pressure, and temperature patterns and their anomalies (also ENSO advisories and discussions). *Climate Diagnostics Bulletin*. No. **97**(1-12) Approximately 80 pp per monthly issue. [Available from U.S. Dept. of Commerce, Washington, DC, 20233.]

Diercks, J.M., R.C. Weir and M.K. Kopper, 1982: Forecast verification and reconnaissance data for Southern Hemisphere tropical cyclones (July 1980 through June 1982). NOCC/JTWC Technical Note 82-1, 77 pp.

Dong, K., 1988: El Niño and tropical cyclone frequency in the Australian region and the northwest pacific. *Aust. Meteor. Mag*., **36**, 219-255.

______, and C.J. Neumann, 1983: On the relative motion of binary tropical cyclones. *Mon. Wea. Rev.*, **111**, pp 945-953

Dunnavan, G.M., 1981: Forecasting intense tropical cyclones using 700-mb equivalent potential temperature and central sea-level pressure. NOCC/JTWC Technical Note 81-1, 12 pp.

Dvorak, V.F., 1975: Tropical Cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103**, pp 420-430.

______, 1984: Tropical Cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11. US Dept. of Commerce, 46 pp.

Gray, W.M., 1978: Hurricanes: their formation, structure and likely role in the tropical circulation. Meteorology over the tropical oceans, Roy. *Meteor. Soc*., pp 155-218.

Guard, C. P., 1997: *Preprints of the 22nd AMS Conference on Hurricanes and Tropical Meteorology, Ft. Collins, CO, May 19-23, 1997*. American Meteorological Society, Boston MA, pp. 476-477.

Guard, C.P., 1983: A study of western North Pacific tropical storms and typhoons that intensify after recurvature. First Weather Wing Technical Note-83/002, 28 pp.

______, and M.A. Lander, 1995: Scale relating tropical cyclone wind speed to potential damage for the tropical Western Pacific Ocean.

Hebert, P.H., and K.O. Poteat, 1975: A satellite classification technique for subtropical cyclones. NOAA Technical Memorandum NWS SR-83, 25 pp.

Holland, G.J., 1980: An analytical model of wind and pressure profiles in hurricanes. *Mon. Wea. Rev*., **108**, No. 8, pp 1212-1218.

Holliday, C.R., and A.H. Thompson, 1979: Climatological characteristics of rapidly intensifying typhoons. *Mon. Wea. Rev*., **107**, No 8, pp 1022-1034.

Jorgensen, D.P., 1984: Mesoscale and convective scale characteristics of mature hurricanes. Part II: core structure of Hurricane Allen (1980). J. Atmos. Sci., 41, 1287-1311.

JTWC, 1960: Typhoon Carmen. 1960 Annual Tropical Typhoon Report, JTWC, 103-108. [NTIS AD 786147.]

______, 1979: Super Typhoon Tip. 1979 Annual Tropical Typhoon Report, JTWC, 72-77. [NTIS AD A082071.]

______, 1993: Illustration of the cloud distribution in a monsoon depression. 1993 Annual Tropical Cyclone Report, JTWC, p 130. [NTIS AD A285097].

______, 1994: Timing of peak intensity with respect to the time of recurvature. 1994 Annual Tropical Cyclone Report, JTWC, Figure 3-03-3, p 51. [NTIS AD A301618]

Lander, 1994a: Description of a monsoon gyre and its effects on the tropical cyclones in the western North Pacific during August 1991. *Weather and Forecasting*, **9**, pp 640-654.

______, 1994b: An exploration of the relationships between tropical storm formation in the Western North Pacific and ENSO, *Mon. Wea. Rev*., **122**, No. 4, pp 636-651.

______, and G.J. Holland, 1993: On the interaction of tropical-cyclone scale vortices. I: Observations. *Quart. J. Roy. Meteor. Soc*., **119**, pp 1347-1361.

Marks, F.D. Jr., and R.A. Houze Jr., 1984: Airborne Doppler radar observations in Hurricane Debby. *Bull. Amer. Meteor. Soc*., **44**, pp 1296-1317.

Matsumoto, C.R., 1984: A statistical method for one- to three-day tropical cyclone track prediction. Department of Atmospheric Science Paper No. 379, Colorado State University, Fort Collins, CO 80523, 201 pp.

Miller, D.W., and M.A. Lander, 1997a: Intensity estimation of tropical cyclones during extratropical transition. JTWC/SATOPS Technical Note 97-002.

Mundell, D.B., 1990: Prediction of tropical cyclone rapid intensification events. Thesis for fulfillment of Master's degree submitted to Colorado State University, Fort Collins, CO 80523, 186 pp.

Ramage, C.S., 1971: Monsoon Meteorology. Academic Press, 296 pp.

Stewart, S.R., and D. Wolff, 1997: Convectively induced mesocyclonic vortices in the eyewall of tropical cyclones as seen by WSR-88D doppler radars. Preprints 22nd Conf. On Hurricanes and Tropical Meteor., Ft. Collins, CO.

______, and S.W. Lyons, 1996: A WSR-88D radar view of Tropical Cyclone Ed. *Weather and Forecasting*, **11**, pp 115-135.

Wakimoto, R.M., and P.G. Black, 1993: Damage survey of Hurricane Andrew and its relationship to the radar-detected eyewall. Proc. 20th Conf. Hurr. and Trop. Meteor., San Antonio, Texas, Amer. Meteor. Soc., pp 54-57.

Weatherford, C.L., 1984: Typhoon structural variability. Colorado State University Atmospheric Science Paper No. 391, 77 pp. [Available from Department of Atmospheric

Science, Colorado State University, Fort Collins, CO 80523.]

Weir, R.C., 1982: Predicting the acceleration of northward-moving tropical cyclones using upper-tropospheric winds. NOCC/JTWC Technical Note 82-2, 40 pp.

Willoughby, H.E., 1990: Temporal changes in the primary circulation in tropical cyclones . *J. Atmos. Sci.*, **47**, pp 242-264.

______, J.A. Clos, and M.G. Shoreibah, 1982: Concentric eye walls, secondary wind maxima, and the evolution of the hurricane vortex. J. Atmos. Sci., 39, pp 395-411.

Wirfel, W.P. and S.A. Sandgathe, 1986: Forecast verification and reconnaissance data for Southern Hemisphere tropical cyclones (July 1982 through June 1984). NOCC/JTWC Technical Note 86-1, 102 pp.

Xu, Y., and C.J. Neumann, 1985: A statistical model for the prediction of western North Pacific tropical cyclone motion. NOAA Technical Memorandum NWS NHC 28, 30 pp.

Zehr, R.M., 1992: Tropical cyclogenesis in the western North Pacific. NOAA Technical Report, NESDIS 61, U.S. Dept. of Commerce, Washington DC, 181 pp.